Experimental Analysis of Mast Lifting and Bending Forces on Vibration Patterns Before and After Pinion Reinstallation in an OH-58 Transmission Test Rig

Edward M. Huff
Computational Sciences Division
NASA Ames Research Center
Moffett Field, CA
ehuff@mail.arc.nasa.gov

Irem Y. Tumer
Caelum Research Corp.
NASA Ames Research Center
Moffett Field, CA

Eric Barszcz
Computational Sciences Division
NASA Ames Research Center
Moffett Field, CA

David G. Lewicki
U.S. Army Research Laboratory
NASA Glenn Research Center
Cleveland, OH

Harry Decker
U.S. Army Research Laboratory
NASA Glenn Research Center
Cleveland, OH

James J. Zakrajsek
Mechanical Components Branch
NASA Glenn Research Center
Cleveland, OH

ABSTRACT

As part of a collaborative research program between NASA Ames Research Center (ARC), NASA Glenn Research Center (GRC), and the U.S. Army Laboratory, a series of experiments is being performed in GRC's 500 HP OH-58 Transmission Test Rig facility and ARC's AH-1 Cobra and OH-58c helicopters. The findings reported in this paper were drawn from Phase-1 of a two-phase test-rig experiment, and are focused on the vibration response of an undamaged pinion gear operating in the transmission. To simulate actual flight conditions, the transmission system was run at three torque levels, as well as two mast lifting and two mast bending levels. The test rig was also subjected to disassembly and reassembly of the main pinion housing to simulate the effect of maintenance operations. An analysis of variance based on the total power of the spectral distribution provides and overview the relative effects of each experimental factor, including strong interactions with torque. Reinstallation of the main pinion assembly is shown to introduce changes in the vibration signature, suggesting the possibility of a strong effect of maintenance on HUMS design and use. Based on these results, further research will be conducted to compare these vibration responses with actual OH58c helicopter transmission vibration patterns.

BACKGROUND

The analysis of transmission vibration is an important aspect of modern helicopter Health Usage and Monitoring Systems (HUMS). It is generally hoped that flight safety can be improved, and maintenance costs reduced, by identifying characteristic damage patterns well in advance of in-flight failures. Transmissions are a major source of noise in helicopter interiors, with most of the noise emanating from the gear mesh [1]. Specifically, gear tooth and shaft deflections, gear tooth profile errors, or gear and bearing misalignment can lead to dynamic loads, and hence vibration and noise. Although several years of diagnostics research has focused on isolating vibration features that are indicative of transmission damage or operating defects, hit-rate performance remains questionable for most real-time metrics, and high false-alarm rates still remain a major impediment for reliable HUMS implementation [2, 3]. The development of integrated research capabilities to address these two aspects of HUMS performance in both test-rig and aircraft environments, respectively, have been reported recently [4, 5].

A likely source of in-flight false-alarms are uncontrolled factors such as pilot maneuvering, extreme aircraft attitudes, and assembly changes induced by routine maintenance operations. All of these factors, and possibly others, introduce complex vibration changes that need to be distinguished from actual defect or damage signatures. In this work, vibration data were collected from GRC's 500HP OH58c transmission test rig to investigate some of these effects. The results were drawn from Phase-1 of a two-phase experiment and are focused entirely on the vibration response of an undamaged pinion gear operating in the transmission test rig. Phase-2 of the experiment will address the propagation of a crack that is seeded into the pinion gear, and will be reported at a later date.

OBJECTIVE

A primary objective of this study was to explore overall changes in vibration patterns, at the input pinion and planetary ring gears, due to forces that are assumed to operate on a transmission during steady state maneuvering. Because the test-rig could be configured to emulate several of these forces, specific attention is focused upon torque, mast lifting and mast bending. Since engine torque is applied rotationally through the input shaft, whereas mast lifting and bending are ap-

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plied externally to the output shaft; these loads are expected to have different types of effects. A second primary objective was to obtain preliminary insight into the manner in which maintenance operations might influence transmission vibrations, independent of maneuvering effects. This was accomplished by performing an input pinion disassembly-reassembly procedure several times, making sure to realign the meshing teeth. In addition to these primary objectives, the data reported here also provide a comparative baseline for data to be collected in Phase 2, which involves disassembly and reinstallation of the main pinion gear with a seeded tooth fault. Here, it is hoped that the baseline data will allow a determination of whether or not the notch filed at the root of a single pinion tooth is itself evident at an early stage. Finally, the baseline data will also be used for direct comparison with flight data that are being collected on ARC's OH-58c helicopter.

METHOD

Apparatus and Instrumentation

An overall schematic of the GRC 500 HP OH-58c test stand is shown in Figure 1, where the helicopter transmission is depicted as part of the test rig. An illustration of the inside of an OH58 helicopter main rotor transmission is shown in Figure 2, where the output shaft (mast), input shaft, and the spiral-bevel input pinion gear of interest are depicted. The characteristics of both are described in detail in earlier literature [1, 6], and are not repeated here. The test rig was instrumented with accelerometers and tachometers, described below, which were interfaced to an eight-channel data acquisition board and an experiment control software package called ALBERT (Ames-Lewis Basic Experimentation in Real Time).[1] The instrumented test rig is shown in Figure 3. Also shown in this picture are: the vertical load cylinder through which lifting force is applied to the mast; the horizontal load cylinder through which bending force is applied to the mast; and, the input shaft through which torque is applied to the transmission.

Using the experiment control software (ALBERT), data were collected at each operational test point for twelve successive 33 sec. periods at 120kHz per channel from five single-axis accelerometers, two tachometers, and a proximity probe. Each 33 sec. period was separated by a 47 sec. period, during which selected raw data files were stored to disk, time-synchronous averages (TSA) were computed and stored, and various summary metrics were calculated and stored. Two of the accelerometers were placed radially and axially to the input pinion shaft, respectively, on a special mounting block permanently attached to the transmission housing. Two accelerometers were also placed in pre-drilled and tapped mounting sites at the 45- and 225-degree positions on the planetary gear housing. A fifth accelerometer was positioned near the 225-degree accelerometer on a special bracket that is later to be used on the Ames OH-58c aircraft[2]. The latter allows for an evaluation of the resonant frequency and transmissivity function of the mounting bracket itself. The two tachometers provided once-per-revolution interrupt signals at the input and output shafts, respectively. These allow convenient time averaging of the various accelerometer signals. The proximity probe is mounted inside the transmission and will be used to detect pinion tooth changes during operation in Phase 2; Phase 1 data will be used for calibration purposes.

All of the analyses discussed in this paper are based on approximately 0.75 sec. segments of the 33-sec time-series data collected from the single-axis accelerometer mounted radial to the input pinion shaft. ALBERT automatically averaged these TSA data over 75 shaft revolutions prior to storage, a process that involves interpolation to an equal number of data points per revolution followed by point-by-point averaging. The 33-sec. recordings that were taken from the ring gear are being used in planetary signal separation analyses, but are not reported here.

[1] General specifications for ALBERT may be obtained from the first author.

[2] Flight safety factors prevent drilling and tapping a transmission housing in operational aircraft.

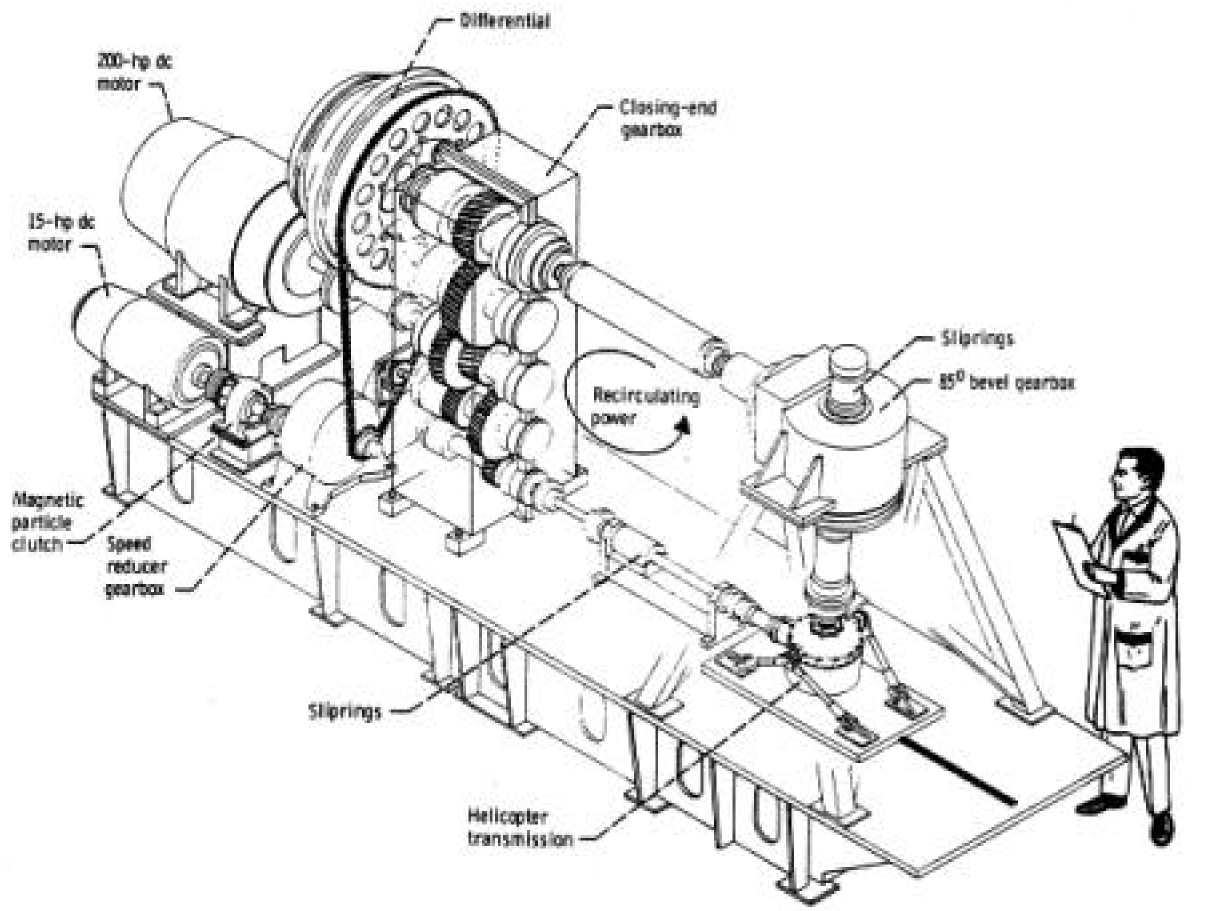

Figure 1. NASA Glenn 500-hp helicopter transmission test stand.

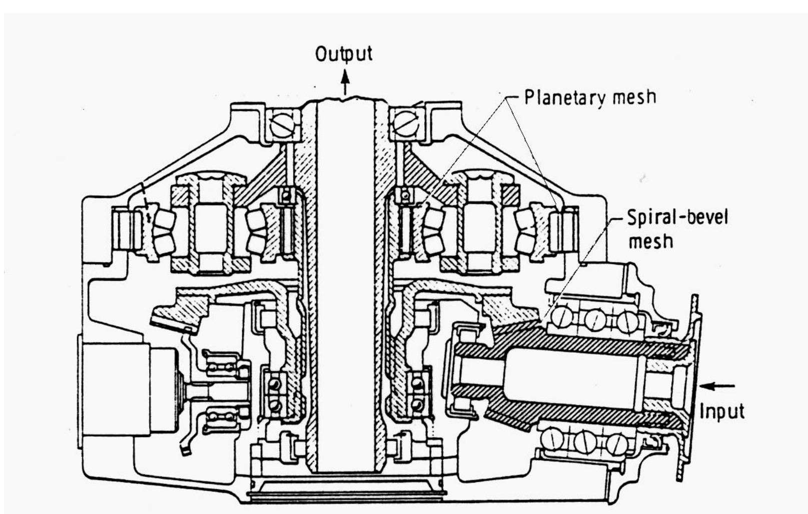

Figure 2. **OH58-A Helicopter main rotor transmission.**

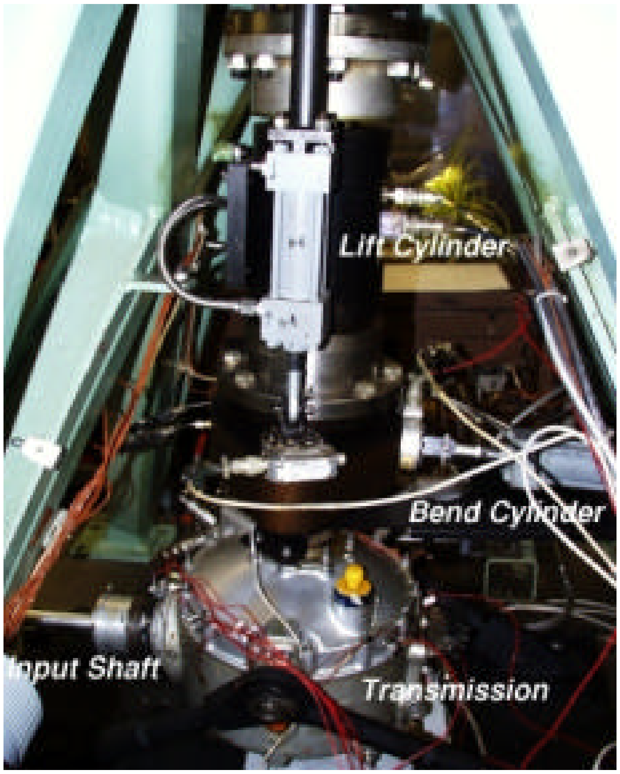

Figure 3. The instrumented OH-58 test rig.

Experiment Design

The experimental design conforms to a four-factor fixed-effects analysis of variance (ANOVA). Factor one represents three levels of torque (40, 80, 100%); factor two represents two levels of mast lifting force (45% and 100%); and factor three represents two levels of mast bending force (off, on). The forth factor, phase, refers to four successive sub-phases of the experiment (1a, 1b, 1c, 1d), which were conducted on separate days. Since each sub-phase required resetting of the test-rig to establish the test points representing the first three factors, the forth factor, in effect, represents successive reconfigurations of the rig.

Starting with Phase 1a, all twelve combinations of the first three variables were run in the order shown in Table 1. For each operating point, twelve TSA records were collected yielding a total of 144 records. In each case, the twelve records are treated as within-cell replications. Due to operational constraints, which limited the amount of randomization that could be done in setting up the rig, in each sub-phase, torque was first established at a given operating level, and then mast-lift and mast-bend manipulated while torque remained constant. Since repeated observations were not made, a potential limitation of the experiment is that the set-point reliability cannot be separated from certain treatment effects. Years of past experience with the rig, however, suggest that this is a small effect.

Table 1: Experimental Treatment Combinations.

Experiment Run Order	Test Operating Point	Torque (% of Max)	Mast Lift (% Max. GW)	Mast Bending (0-off, 1-on)
1	1	40 %	45 %	0
2	2	40 %	45 %	1
4	3	40 %	100 %	0
3	4	40 %	100 %	1
5	5	80 %	45 %	0
6	6	80 %	45 %	1
8	7	80 %	100 %	0
7	8	80 %	100 %	1
9	9	100 %	45 %	0
10	10	100 %	45 %	1
12	11	100 %	100 %	0
11	12	100 %	100 %	1

In addition to repeating all of the twelve test conditions, the sub-phases differed in several other respects. Between Phases 1a and 1b, and again between Phases 1c and 1d, the main pinion was first disassembled and then reinstalled into the transmission.[3] This procedure was intended to allow at least a cursory evaluation of the effect that a routine maintenance inspection of the main pinion gear might have on the transmission's vibration pattern. Because it was recognized that set-point reliability of the test rig is a confounding factor, as mentioned above, between Phases 1b and 1c no pinion reinstallation was performed. Thus, except for day-to-day variations in the test rig, Phases 1b and 1c might be expected to be more similar to each other than either of them to Phases 1a or 1c. Finally, it should be noted that between Phases 1c and 1d certain maintenance corrections were made to the test rig itself, the effects of which are unavoidably confounded with the reinstallation and reliability effects already present in the data. Conjectured statistical differences based on these particulars are addressed as "pre-planned comparisons."

RESULTS

In the statistical analyses presented below, it is generally assumed that the effects of experimental treatments will be revealed, at least at a first-order level, in the power spectra of the time-series records. It is further assumed that although it is mathematically possible for the total power of a spectrum to change, while the relative spectral distribution remains constant, in practice this is not likely to happen. For this reason the total power of the frequency spectrum—which is equivalent to the RMS^2, or variance, of the time-domain series—is used as the dependent variable in the analyses.[4] In particular, Scheffé's method for testing the equivalence of sample variances with analysis-of-variance (ANOVA) is used [7], which is done by first computing the natural logarithm of total power.

Analysis of Spectral Energy

To provide an overview, Figure 4 shows the total power (millivolts^2) from the spectral distributions for each experimental test condition and replication. The data may be converted to g-levels based on the approximation that 1g = 11.4 mV. It is evident that both torque and sub-phase have major effects on total power. At 40% torque, all of the treatment combinations look very similar in total energy. By contrast, higher torque levels (80% and 100%) show marked treatment differences and an increasingly wide range from one sub-phase to another. With regard to sub-phase effects, at the higher torque levels there is some suggestion that Phases 1b and 1c are more similar to each other than to either Phase 1a or 1d. In addition, it is notable that at higher torque levels Phase 1d has a much *lower* total spectral energy than any other sub-phase. This may be due to reassembly or the fact that major maintenance adjustments were made to the test rig after Phase 1c. Which of these factors is primarily at play should become more evident when the rig is run again during Phase-2 of the experiment, with the notched pinion installed.

Figure 5 shows *representative* spectral distributions based on the first treatment replication from each condition run during Phase 1a.[5] The x-axis represents frequency bins in terms of shaft orders. In this particular case the pinion mesh frequency is located at bin 19—because there are 19 teeth in the pinion gear—and the second, third, and fourth mesh harmonics are located at bins 38, 57, and 76, respectively. It should be noted that the scale of the y-axis is an order of magnitude lower for the 40% torque level, which tends to mask the fact that spectral energy is extremely low. The charts do convey the correct impression, however, that the spectral distribution is more evenly spread among the mesh harmonics at 40% torque, and that there is a dominant peak at bin 25. Although it is presently unclear to the authors why this peak occurs at bin 25, further examination has shown that it retains roughly the same absolute level of energy at the 80% and 100% torque levels, which is not apparent due to the different scale. It is clear that the most over-riding effect of increasing torque is to increase the relative magnitude of the mesh frequency itself. Moreover, the spectral plots support the contention that changes in total power are accompanied by changes in the relative spectral distribution.

[3] Care was taken to align the same meshing teeth before and after installation. Misalignment is another possible source of pattern change in real HUMS.

[4] Since the mean of acceleration signal is zero, RMS^2 is equivalent to the variance of the series.

[5] Spectral averaging was not felt to be necessary due to the strong similarity of spectral distributions between replications.

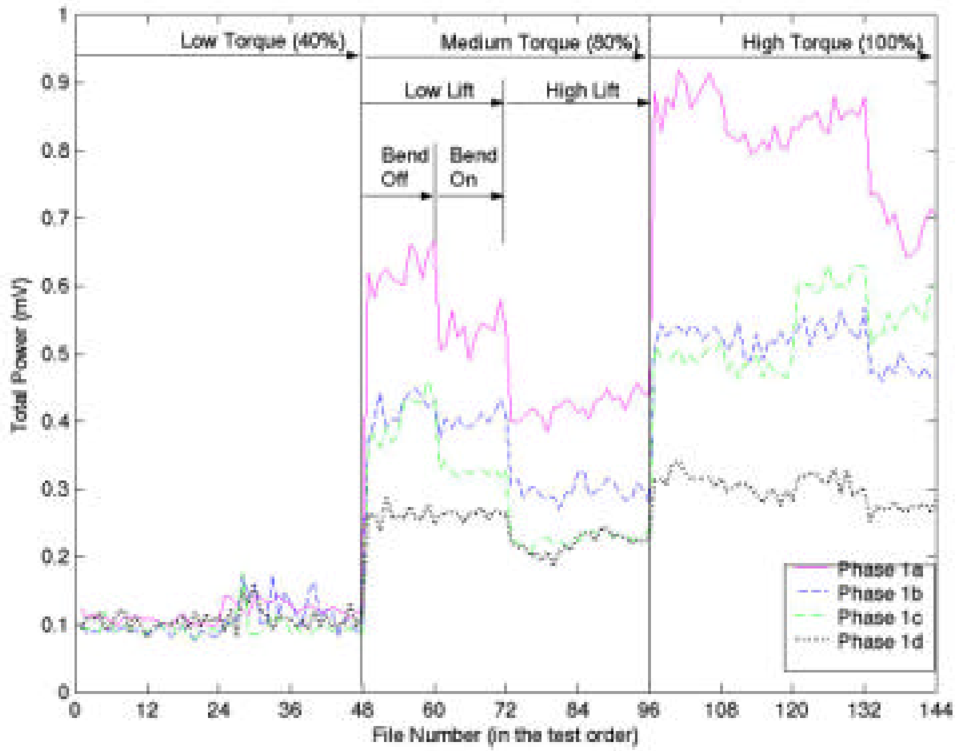

Figure 4. Comparison of Total Power for all treatment conditions.

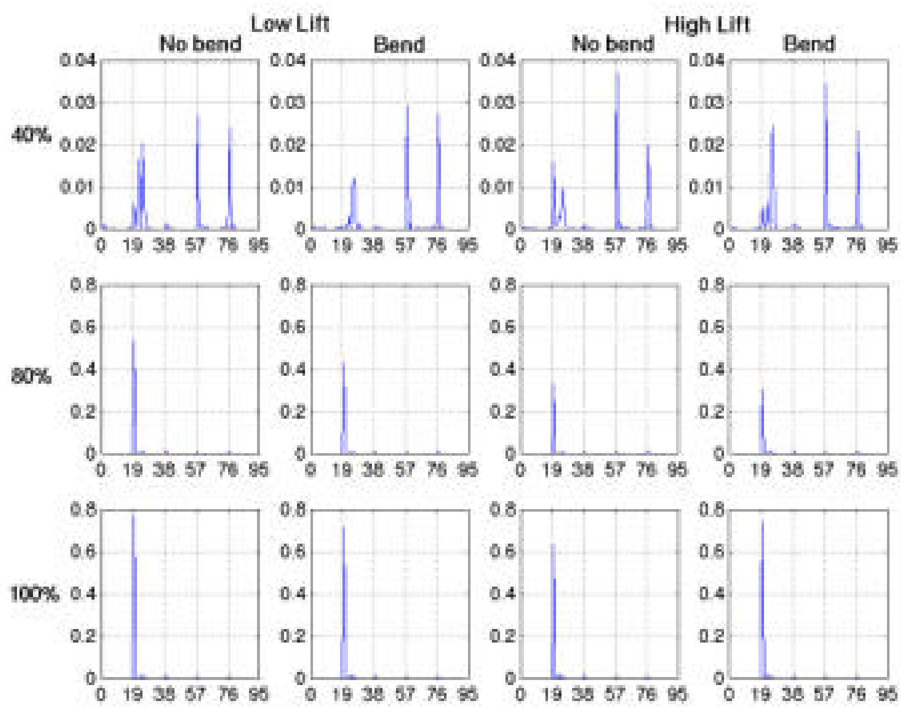

Figure 5. Typical Frequency Content for Test Conditions (Replication 1, Phase 1a.)

Analysis of Variance

A complete four-way fixed effects analysis-of-variance (ANOVA) using Scheffé's procedure is shown in Table 2. This model simply partitions the squared deviations from the grand mean as follows:

Total SS = Treatment SS + Interaction SS + Residual

The model therefore has the advantage of providing a descriptive overview of how variance is partitioned across the experiment. Referring to the "Percent Total SS" column, as previously seen in Figure 4, torque is by far the most dominant factor and accounts for 83.43% of the total variance. The next most important factor is sub-phase, which accounts for 8.78%. The remainder of the variance is distributed between the various interactions, which collectively account for 6.38% of total sum of squared deviations. Error, or residual variance, is slightly over 1%, and is attributable to within-cell differences between replications.

It should be kept in mind that because of the large number of degrees of freedom, even small main effect and interaction terms are "significant" at $\alpha = .01$. In general, significant effects that account for less than 0.05% of the Total SS may be considered much less important than, for example, the two-way interactions between torque and phase, and torque and lift, which account for 3.9% and 1.72% of the Total SS respectively. A three-way interaction between torque, phase, and lift is also notable in accounting for 0.45% of variance. Relatively large, significant interactions such as these, all of which involve torque, clearly indicate that the effects of the phase, lift and bend differ depending upon which level of torque is chosen as a reference. For this reason, separate three-way ANOVAs were performed next at each torque level.

Table 2: Four-Way Analysis of Variance for Total Experiment.

Source of Variation	Sum of Squares	Percent Total SS	DF	Mean Square	F
Main Effects	283.060	92.60	7	40.437	6852.481*
TORQUE	255.037	83.43	2	127.519	21609.289*
PHASE	26.851	8.78	3	8.950	1516.737*
LIFT	0.573	0.19	1	0.573	97.103*
BEND	0.599	0.20	1	0.599	101.473*
2-Way Interactions	17.476	5.72	17	1.028	174.207*
TORQUE PHASE	11.927	3.90	6	1.988	336.852*
TORQUE LIFT	5.250	1.72	2	2.625	444.858*
TORQUE BEND	0.138	0.05	2	0.069	11.718*
PHASE LIFT	0.082	0.03	3	0.027	4.610*
PHASE BEND	0.079	0.03	3	0.026	4.451*
LIFT BEND	0.000	0.00	1	0.000	0.078
3-Way Interactions	1.962	0.64	17	0.115	19.560*
TORQUE PHASE LIFT	1.385	0.45	6	0.231	39.116*
TORQUE PHASE BEND	0.098	0.03	6	0.016	2.761
TORQUE LIFT BEND	0.442	0.14	2	0.221	37.414*
PHASE LIFT BEND	0.038	0.01	3	0.013	2.147
4-Way Interactions	0.071	0.02	6	0.012	1.999
TORQUE PHASE LIFT BEND	0.071	0.02	6	0.012	1.999
Explained	302.569	98.98	47	6.438	1090.924*
Residual	3.116	1.02	528	0.006	
Total	305.685	100.00	575	0.532	

* Sig. at $\alpha = .01$

Table 3: Three-way Analysis-of-Variance at each Torque Level.

Source of Variation	DF	40% Torque Sum of Squares	40% Torque Percent Total SS		80% Torque Sum of Squares	80% Torque Percent Total SS		100% Torque Sum of Squares	100% Torque Percent Total SS	
Main Effects	5	2.171	40.86	*	18.743	93.34	*	24.425	96.72	*
PHASE	3	1.054	19.84	*	13.77	68.57	*	23.954	94.85	*
LIFT	1	0.877	16.51	*	4.946	24.63	*	0.001	0.00	
BEND	1	0.239	4.50	*	0.027	0.13	*	0.471	1.87	*
2-Way Interactions	7	0.532	10.01	*	0.913	4.55	*	0.641	2.54	*
PHASE LIFT	3	0.433	8.15	*	0.516	2.57	*	0.517	2.05	*
PHASE BEND	3	0.021	0.40		0.115	0.57	*	0.04	0.16	*
LIFT BEND	1	0.078	1.47		0.281	1.40	*	0.083	0.33	*
3-Way Interactions	3	0.009	0.17		0.091	0.45	*	0.01	0.04	
PHASE LIFT BEND	3	0.009	0.17		0.091	0.45	*	0.01	0.04	
Explained	15	2.711	51.03	*	19.746	98.33	*	25.075	99.29	*
Residual	176	2.602	48.97		0.335	1.67		0.179	0.71	
Total	191	5.313	100.00		20.081	100.00		25.254	100.00	

* Sig. at $\alpha = .01$

The results of the separate 3-way ANOVAs are summarized in Table 3, where only the essential columns are retained to show the important sum of squares information. Again, "significant" effects should be regarded cautiously given the large number of degrees of freedom. As torque increases, it may be seen that the percentage of TOTAL SS accounted for by Phase increases dramatically from 19.84% (at 40% torque) to 94.85% (at 100% torque). At the two lower torque levels, mast lift accounts for 16.51% and 24.63% of variance, respectively, while at the 100% torque level, it has no apparent effect at all. Mast bend, on the contrary, remains at a very low level of influence throughout. It is apparent, therefore, that of the two, mast lift can have a much stronger influence on vibration patterns than mast bend, a fact that is suppressed in the overall ANOVA (Table 2) because of the torque-lift interaction.

It is noteworthy that at the lowest torque level not only was the degree of variability (i.e., Total SS) much lower than at the two higher levels, but also a much lower percentage of this variance was *explained* by the treatment effects. Treatment effects at the 40% torque level explained roughly half of the variance (51.03%), while virtually all of it was explained at the two higher levels (98.33% and 99.29%). In short, the 40% torque condition contained the largest amount of experimental "noise."

Because phase was clearly the most important factor at each level of torque, and also because it interacted with lift at each level, separate one-way ANOVAs were performed to examine differences between phases. It may be recalled that there is *a priori* reason to believe that Phases 1b and 1c should look more similar to each other than to Phases 1a or 1d, because no reinstallation of the pinion was made between Phases 1b and 1c. By the same token, there is some reason to suspect that Phase 1d should look different from the others because an unavoidable maintenance change was made to the test rig before that phase was conducted.

All three one-way ANOVA tests of the sub-phase means at each torque level were highly significant. Based on the *a priori* conjectures about inter-phase differences, four pre-planned comparisons were performed using the *t* statistic and are summarized in Table 4. Each comparison reflects a different underlying null hypothesis. The "contrast values" in the table are computed by taking a weighted linear sum of the phase means subject to the constraint that the weights sum to zero. Based on the null hypothesis in each case this value should be normally distributed with a mean of zero.

Table 4: Pre-Planned Comparisons of Phase Means at Each Torque Level.

			40% Torque		80% Torque		100% Torque	
Contrast Number	Contrast Null Hypotheses	D.F.	Contrast Value		Contrast Value		Contrast Value	
1	Phase 1b - Phase 1c = 0	188	0.092	*	0.197	*	-0.036	
2	Phase 1a - Avg. Phases (1b, 1c) = 0	188	0.324	*	0.887	*	0.866	*
3	Phase 1d - Avg. Phases (1b, 1c) = 0	188	0.148	*	-0.558	*	-1.123	*
4	Phase 1d - Avg. Phases (1a, 1b, 1c) = 0	188	-0.060		1.280	*	2.117	*

* Sig. at $\alpha = .01$

Contrast 1 evaluated the hypothesis that Phase 1b and 1c means are equal. Contrary to what might have been hoped, the small differences in mean reflected in the contrast values were significantly different from one another at the lower two torque levels. This suggests that day-to-day variation in test-rig performance may influence vibration results to some extent. At all three torque levels, however, the averages of Phases 1b and 1c were consistently different from Phase 1a (contrast 2) and Phase 1d (contrast 3), which supports the general thesis that the process of pinion reinstallation did, indeed, have a measurable effect on vibration response. Contrast 4, however, found that at the two higher torque levels Phase 1d was appreciably different than the averaged means for Phases 1a, 1b, and 1c—which confirms that the test rig modification also had a significant effect.[6]

CONCLUSIONS AND FUTURE WORK

Do the forces that operate on the transmission during maneuvering—such as torque, mast lifting, and mast bending—influence overall vibration patterns in a consistent way? Will routine maintenance operations, such as inspecting the main input pinion, change the vibration pattern even though the gear is found to be satisfactory and simply replaced? These questions were addressed on a preliminary basis in this study.

Unfortunately, because of operational constraints, repeated observations of the twelve treatment combinations (i.e., operating points) could not be accomplished during each testing session, and, therefore, it is not possible to say with conviction how much the inherent variability of the test-rig contributed to the present findings. Some evidence that it is a minimal effect is provided by the first pre-planned comparison, discussed above, between Phase 1b and 1c.

Over and above torque, which has a very large and systematic effect on the vibration spectra, there is clear evidence that mast lifting also has a significant influence, which is seen at lower operating torque levels but not when torque reaches the 100% limit. With regard to HUMS design, this implies that the operating gross-weight of the vehicle, or maneuvers which produce equivalent mast lifting forces, should be factored into real-time diagnostic computations, because this will effect the observed vibration signatures. Mast bend has a smaller by identifiable effect on the vibration signature, which appears to be independent of the torque level. This variable might be expected to play an important role in helicopter designs that produce sizeable shaft bending moments, such as rigid rotor systems. In the case of the OH-58, which has a teetering rotor, it may be a minimal consideration—but still one that could be predicted from known maneuvering states and computed in conjunction with mast lift.

With regard to the simple maintenance inspection effect that is emulated in this experiment, the jury is still out. There is very clear evidence, of course, that reconfiguration of the test rig produces significant changes in vibration performance, but it is not possible to isolate the underlying reasons. Based on the current data we must simply conclude that pinion reinstallation, operating point variability, and rig maintenance effects, probably all played a part in the inter-phase differences that were observed. If future research confirms that component re-installations strongly influence the vibration signature, however, the implication for HUMS is that post-maintenance calibration and parameter identifications will be a necessary aspect of the system initialization process. There might also be issues to deal with concerning the extent to which patterns characteristic of a particular transmission before inspection can be used to evaluate its health after inspection.

Finally, the analyses presented in this report are limited to the synchronously averaged data collected from the single radial accelerometer located near the input pinion. Averaging was done as a method of choice in preparation for Phase 2, where this same channel will be used for studying seeded crack propagation. It is

[6] It is helpful to use the absolute contrast value to appreciate the extent of the effect.

notable that in performing synchronous averaging, however, that the RMS of the signal was considerably reduced, including some instances of more than an order of magnitude. This leaves open the general possibility that important spectral changes were masked by the averaging procedure, which will be analyzed further in the laboratory using the raw data from both pinion channels.

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